Chapter

Drugs and Biodiversity Loss: Narcotraffic-Linked Landscape Change in Guatemala

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Abstract

Characteristic of the Anthropocene, human impacts have resulted in worldwide losses in forested land cover, which can directly and indirectly drive biodiversity loss. The global illicit drug trade is one source of deforestation directly implicated with habitat loss in Central America, typically for drug trafficking and livestock production for money laundering. Given reports of deforestation in Central America linked to narcotraffic, we explored vegetation changes within Guatemala's highly biodiverse Maya Biosphere Reserve by examining trends suggestive of deforestation in a protected area. As such, we collected satellite-derived data in the form of enhanced vegetation index (EVI), as well as history of burned areas, published human-"footprint" data, official population density, and artificial light activity in Laguna del Tigre National Park from 2002 to 2020 for descriptive analysis. We found consistent reductions in EVI and trends of anomalous losses of vegetation despite a baseline accounting for variation within the park. Analyses revealed weak correlations ($R^2 \leq 0.26$) between EVI losses and official sources of anthropogenic data, which may be attributable to the data's limited spatial and temporal resolution. Alarmingly, simple analyses identified vegetation losses within a protected area, thus emphasizing the need for additional monitoring and science-based, but interdisciplinary policies to protect this biodiversity hotspot.

Keywords: deforestation, narcotrafficking, biodiversity loss, money laundering, habitat, enhanced vegetation index

1. Introduction

Drug trafficking and money laundering via livestock production contribute to deforestation directly implicated with habitat loss in Central America [1, 2]. In light of reports of deforestation in Central America being connected to narcotrafficking, we examined trends suggestive of deforestation within Laguna del Tigre National Park in Guatemala's highly biodiverse Maya Biosphere Reserve. Our explorations are generalizable and use openly accessible data sources, encouraging transference of our descriptive analyses to other study areas with limited resource availability or safety concerns precluding abilities to collect data *in situ*.

Global biodiversity is being lost at an unprecedented rate creating a critical environmental crisis [3]. The world's biodiversity is concentrated in hotspots–regions with spectacularly high levels of species richness and endemism. Nearly half the world's vascular plant species and one-third of terrestrial vertebrates are endemic to 25 such hotspots [4, 5]. Historically, biodiversity hotspots covered 12% of the land's surface, but even by 2003, their intact habitat covered only 1.4% of the land [6]. None of these hotspots have more than one-third of their original pristine habitat remaining [5].

Tropical forests account for the majority of all biodiversity hotspots [4]. Yet as well as the highest species richness, in tropical forests, we also find some of the most acute human pressures on natural environments [7]; the conservation of tropical forests being the most pressing biodiversity issue today. Tropical evergreen and deciduous forests spanned ~17 million km^2 globally but have now declined to ~11 million km^2 [8]. Such forests are expected to continue to shrink further this century, with 11–36% of forests existing in 2000 projected to disappear by 2050 [8, 9]. Main drivers of biodiversity loss in tropical ecosystems are related with the conversion of tropical forest to intensive agriculture or ranch cattle fields, forest fires, mining, logging, hunting, and illegal trade [10–14]. Over half of tropical or subtropical forests still in existence today have been substantially altered. Indeed, a quarter of the remaining tropical rainforest has been fragmented, with one-fifth of these forests selectively logged at some level from 2000 to 2005 [8].

Mesoamerica is one of three global tropical forest biodiversity hotspot regions that have lost much of their forested area over the last 30 years (others being Sundaland—all of Indonesia and Indo-Burma) [15]. Central America—part of the Mesoamerica region—covers only 2% of the world's territory but is home to 12% of the planet's biological diversity [16]. For example, the Central American country of Guatemala has 2779 species identified by the International Union for the Conservation of Nature (IUCN), of which 189 species are listed as threatened [17]. Unfortunately, research effort in this megadiverse country is poor, especially for hyper-diverse taxa, which has higher number of species and endemism in the tropics [4, 18], and biodiversity research is disproportionately focused on temperate regions [17].

Through means of drug-crop cultivation or trafficking, the global illicit drug trade is a major driver of tropical forest loss, termed "narco-deforestation" [2]. Drug-crop cultivation has played a disproportionately large role in deforesting and degrading some of the world's most biodiverse ecosystems, including those in national parks and indigenous territories [19, 20]. Drug trafficking is also associated with deforestation and habitat degradation in Central and South America [2, 21, 22]. However, due to their remoteness, large tracts of contiguous forest can equally be beneficial for concealing illicit activity, drawing narcotrafficking operations to biodiversity hotspots [23]. In general, land conversion to directly support trafficking efforts is a relatively small portion of the impact of the drug trade on biodiversity; however, as an order to launder profits, traffickers convert vast tracts of forest landscapes to agricultural enterprises, such as cattle ranches and oil palm plantations, as a modus operandi to conceal financial transactions [20, 24].

Cocaine trafficking in Honduras, Guatemala, and Nicaragua is estimated to account for between 15% and 30% of annual forest loss in these three countries over the past decade, and 30–60% of loss occurred within nationally and internationally designated protected areas [24]. Associated deforestation could be driven directly as a product of drug-movement (e.g., creation of illegal aircraft landing strips and pathways out) or indirectly via "drug-ranches"—a front of ranching and concealed money laundering as mentioned above.

Among Central America's protected areas, narco-deforestation has impacted Guatemala's Maya Biosphere Reserve and La Mosquitia, at the border between Honduras and Nicaragua; and to a lesser extent, the Jiquilisco region in El Salvador, the Osa peninsula in Costa Rica, and Darién National Park in Panama [16]. Cattle ranch laundering might be facilitated in northern Guatemala due to the low presence of law enforcement agencies for border security [25], increase of illegal economies and clandestine routes through the border [26], low control of cattle monetary transactions [1], the increase of narco-airstrips since mid-2000s [27], and corruption [28].

Here, we explore forest loss trends in Guatemala's Laguna del Tigre National Park—an area with a history of increasing narcotrafficking and the core zone of the Maya Biosphere Reserve, Guatemala's largest protected area complex. Recent large-scale drug trafficking interdiction, such as the US "War on drugs," has shifted international supply lines from previous shipping channels through the Caribbean or Pacific direct to Mexico, to now passage overland through Central America [29]. We identify spatial aggregations of deforestation, as well as their magnitude and extent using vegetation data derived from satellites. Our results demonstrate a fine-scale baseline of narco-deforestation in Guatemala's largest and most pristine protected area.

2. Methods

2.1 Study area

The Laguna del Tigre National Park (LTNP) is part of a conglomerate of protected areas together known as Maya Biosphere Reserve (MBR). This tropical humid forest extends through the Yucatan Peninsula in northern Guatemala, southeast Mexico, and northern Belize (**Figure 1**). LTNP occupies 3379 km^2 composed mainly of tropical rainforest, pastures, and wetlands [30], being one of the largest inland RAMSAR sites in Mesoamerica [31]. The altitude of the LTNP ranges from 60 to 182 m, the weather is hot (25–35°C) and humid (85%), and annual precipitation reaches 1629 mm. Within the National Park boundaries live already regionally or globally endangered vertebrate species such as jaguar (*Panthera onca*, (Linnaeus 1758)), cougar (*Puma concolor*, (Linnaeus 1771)), Geoffroy's spider monkey (*Ateles geoffroyi*, (Kuhl 1820)), Harpy eagle (*Harpia harpyja*, (Linnaeus 1718)), Mealy parrot (*Amazona guatemalae*, (Sclater 1860)), Morelet's crocodile (*Crocodylus moreletii*, Duméril & Bibron 1851), tapir (*Tapirus bairdii*, Gill 1865), scarlet macaw (*Ara macao*, (Linnaeus 1758)), Spectral bat (*Vampyrum spectrum*, (Linnaeus 1758)), and Yucatán black howler monkey (*Alouatta pigra*, (Lawrence 1933)) [32–34]. LTPN also hosts endangered tree species such as *Dalbergia stevensonii* (Standl 1927; IUCN: Critically endangered) and *Swietenia macrophylla* (King 1886; IUCN: Vulnerable) [35, 36]. In addition to wildlife conservation, Maya Biosphere Reserve is part of the Yucatan basin—the development center of Mayan civilization (approx. 800 BC–900 AD), holding several archeological sites, some of them recognized within the World Heritage Convention.

Massive immigration and extensive deforestation occurred in the Petén basin in the last three decades of the twentieth century [37]. Immigration to northwestern Petén was pushed during the 1980s by poverty and civil war [38], further, during the mid-1980s and 1990s, forests were cleared for establishing subsistence farming, roads, and maize [39]. Later in the early 2000s, forest clearance increased even more in northwest Petén, especially in LTNP, for the establishment of ranching fields

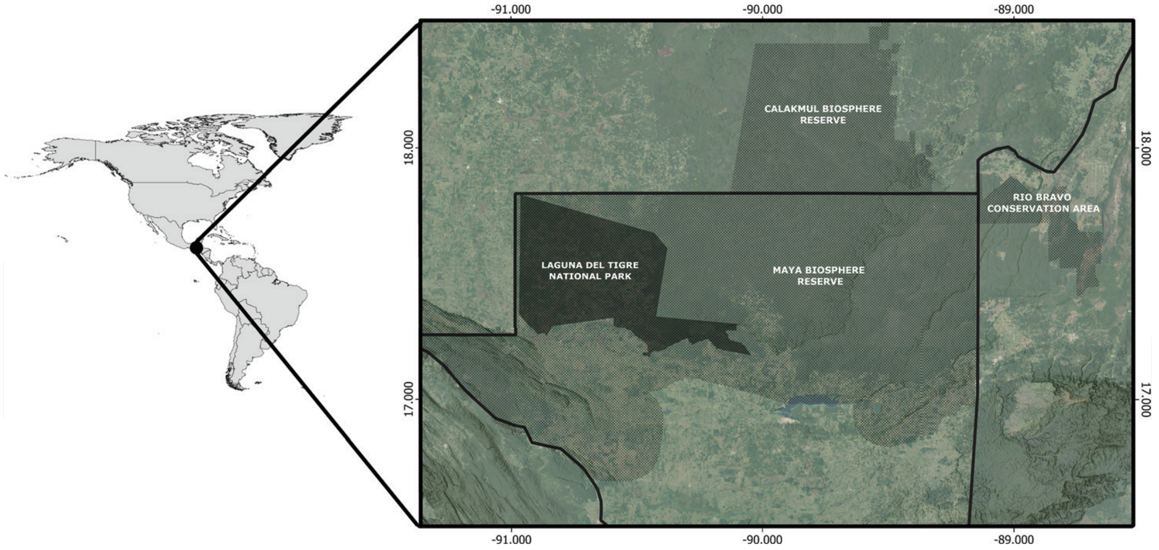

Figure 1.
Map of contiguous protected areas from Guatemala, Mexico, and Belize. Laguna del Tigre National Park (dark shaded) is part of a complex of protected areas immersed within the Maya biosphere reserve (2,090,667.00 ha) at western border. LTNP became part of the RAMSAR convention sites in 1990 for promoting the conservation of 335,060 ha. Illegal activities during the last three decades have been shifting natural ecosystems into ranchery fields.

related to illegal activities that overpass the capacities of governmental institutions in charge of the protection of the environment or cultural heritage (for example, Ministry of Environment, National Council of Protected Areas, or the Institute of Anthropology and History) [29].

2.2 Landscape data collection

Remotely sensed vegetation indices quantify spectral signatures (i.e., variations in wavelength reflectance) found in photosynthetically active radiation, and correlate with coarse scale landscape conditions that vary with soil type, precipitation, elevation, and temperature gradients [40]. Vegetation indices also correlate with vegetative primary productivity, which lend to their application in ecological research [41], and demonstrate the impact from land cover change on biodiversity [42]. The enhanced vegetation index (EVI) is a widely used measure of vegetation phenology that is sensitive to increased biomass and variation in canopy cover [43, 44], making it ideal in assessing land cover change in tropical landscapes [45].

The Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard NASA's Terra satellite collects multispectral data worldwide, including data on vegetation phenology in the form of vegetation indices [46]. The MODIS sensor collects EVI data at 250-meter spatial resolution and 16-day temporal resolution. Values for EVI span from −1, representing no vegetation, to 1, corresponding to high vegetative biomass [44].

Fire regimes are natural in many terrestrial ecosystems [47]. Fires can fluctuate in tropical Central America because of climatic phenomena (i.e., El Niño-Southern Oscillation) inducing drought with varying magnitudes [48], and between ecoregions, with fires typically less common in tropical humid forests (i.e., the ecoregion of northern Guatemala [49]). Nevertheless, smaller fires more commonly associated with human activities have amassed to significant burned areas in Central America [48], including northern Guatemala [49].

The MODIS sensor can also quantify whether burn-sensitive vegetation has undergone uncharacteristically permanent changes, consistent with recent history of burning, and statistical algorithms have been developed to binarily categorize these areas as either "unburned" or "burned," with values of 0 or 1, respectively [50]. Data are collected on burned areas at 500-meter spatial resolution and averaged monthly [50]. We collected MODIS data at the finest available resolution (i.e., 250-meter resolution EVI and 500-meter resolution burned area) for Guatemala spanning years 2002–2020 collected seasonally using the *MODIStsp* R package [51] from April 1 until April 30, which correspond to the Guatemala's summer season, when clear skies result in low image obstruction due to clouds, rain, and oversaturation of soils reflecting artifactual water bodies.

Radiance from artificial, nighttime lights has been associated with human settlements [52]. In addition to being used to monitor expansions in urban development [53, 54], artificial light has been shown to identify local-level development in rural areas [55]. Artificial light data can provide information on human populations where official reporting may not be conducted or unreliable [55]. The Visible Infrared Imaging Radiometer Suite (VIIRS) sensor aboard NASA's Suomi NPP satellite records radiance observed from nighttime lights [52, 56]. Radiance is recorded as a continuous measurement of nanowatts per steradian per square meter (nW cm^{-2} sr^{-1}), where values range from 0 (no radiance detected) to 255 (highest radiance). We collected 2012 nighttime light data at 30-meter spatial resolution with the use of imagery from the NASA Worldview application [57].

Human influences in natural areas have been shown to impact biodiversity [58], enhance extinction risk [59], and promote colonization of invasive species [60]. The human footprint is a cumulative and multivariable metric used to quantify humans' indirect and direct effects on wilderness areas [61]. High human pressures have been quantified in areas with higher biodiversity [62], and a recent assessment identified that the majority of Guatemala was highly human-modified [63], emphasizing scarcity of wilderness areas in the country.

A standardized, quantitative analysis combined human-related pressures (e.g., major road and waterways, crop and pasture lands, built areas, and human population density, among other variables) to create a global map of the human footprint, which was validated via satellite imagery [62]. We utilized this published 1-kilometer spatial resolution rasters of the 2009 assessment of the global human footprint [62]. Human footprint is measured on a scale from 0 (no human influence) to 100 (highest degrees of human influence).

2.3 Data analysis

We prepared EVI raster data for descriptive analyses by cropping and masking data from MODIS tiles to the extent of LTNP. We generated 19 annual EVI rasters by averaging the two rasters collected from April 1 to April 30 from each year, then using these averages to represent annual EVI values spanning the 19-year study period (i.e., 2002–2020). All raster calculations were performed in R [64], using functionality in the *raster* package [65]. Visualizations were performed using the *raster*, *rasterVis*, and *plotfunctions*, and *rgdal* R packages [65–67].

We examined changes in annual EVI values over time by calculating the annual difference in annual EVI values from 2002 (i.e., the initial collection year), as well as in annual timesteps (e.g., 2008 EVI values subtracted from those in 2007). Next, we evaluated the magnitude of annual EVI change from 2002 by converting the differences in annual EVI values from 2002 into percentages of the initial values. That is, pixel-level percentages were calculated by subtracting each year's EVI raster values from 2002's raster values, then dividing their difference by the absolute value of the 2002 raster, and multiplying decimals by 100. We examined the distribution of areas with loss and gain in EVI by isolating net positive and net negative percent changes and averaging raster values.

Next, we examined each year's mean EVI values for anomalies (i.e., values deemed uncharacteristically high or low relative to variation during a defined baseline period). Specifically, we adapted a formula for calculating anomalies in climatic phenomena [49, 66, 68], which essentially calculates a z-score transformation common in statistics for understanding the measure of standard deviations that a sample is away from its mean [69]. Using the first 5 years (i.e., 2002–2006) as the baseline, annual anomalies (A_i) were calculated from subtracting each of the 14 annual mean EVI rasters during 2007–2020 ($\bar{X}_i$) from the baseline years' mean raster ($\bar{X}_b$) and dividing the difference from the raster characterizing the standard deviation in EVI during baseline years (σ_b) (Eq. (1)). We calculated a cumulative anomaly raster to understand the geographic distribution of the overall magnitude of anomalies and where uncharacteristic values have been found.

$$A_i = \frac{\bar{X}_i - \bar{X}_b}{\sigma_b} \tag{1}$$

Finally, we assessed fire and published human data for co-occurrence and relationships with changes in EVI. To understand fire data, we collected monthly MODIS and cropped images to the study area extent and summarized the magnitude of burned areas from 2002 to 2020 by calculating the sum of all binary (i.e., burned or unburned) rasters collected. Finally, we transformed continuous rasters into four categories of magnitude of burned areas (i.e., none, low, moderate, and high) using natural breaks (Jenks). We did not alter other published data sources. Percent EVI change rasters were examined for simple correlations between burned areas, 2009 human footprint data, and 2012 artificial light raster data within Laguna del Tigre National Park.

3. Results

Our results indicate there was considerable variation in the percent change of EVI in LTNP over the study period of 2002–2020. We found percent loss of EVI over broader geographic areas than percent gained, pixels of which were aggregated in the southern extent of the national park (**Figure 2A**). Similarly, for EVI percentages relative to 2002, the majority of values were negative for most (63%) years indicating negative changes (**Figure 2B**). When comparing differences in raw EVI values at annual timesteps, we noted considerable variation between years (**Appendix Figure A1**); however, the culmination of these differences manifested as signals of EVI loss consistently throughout the national park (**Figure 3**). We noted the geographic distribution of higher annual percent gain in reference to 2002 occurred along the southern extent of the park; however, high

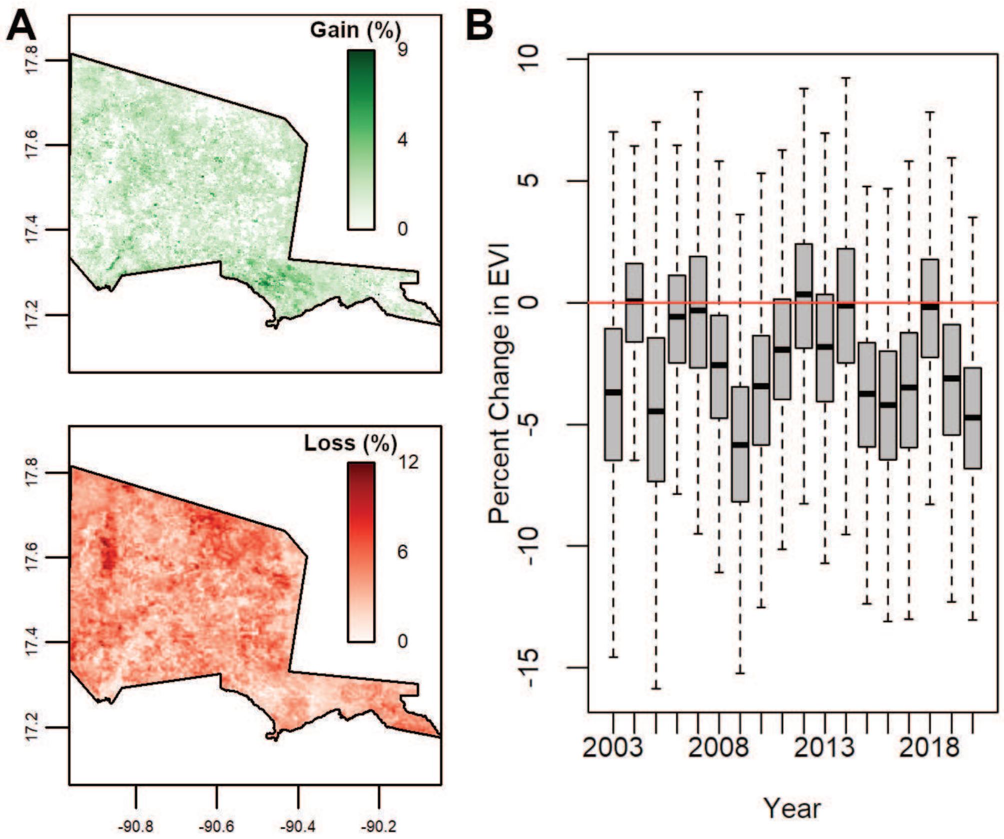

Figure 2.
Percent change in EVI from 2002 within Laguna del Tigre National Park. Annual EVI values from 2003 to 2020 were converted to percentages relative to 2002 and averaged into maps. A) Maps were isolated to increases (top) and decreases (bottom) in EVI percentage. Larger, widespread areas experienced more EVI percent loss (i.e., darker red colors in bottom panel) relative to clustered areas with strong increases in EVI (i.e., smaller dark green areas in top panel). B) Boxplots represent percent change in EVI values relative to 2002 (y-axis) grouped by year (x-axis). Red horizontal line represents no change (i.e., values consistent with 2002). Note the majority of values as denoted by boxplots are below the red line for nearly all years indicating negative changes in EVI percentages relative to 2002.

percent loss in reference to 2002 occurred throughout the national park, with more pronounced in areas adjacent to the Guatemala-Mexico border (**Appendix Figure A2**).

Trends were noted of negative anomaly values consistent with uncharacteristic EVI loss in most years. Some geographic similarities in anomalies were found between years (i.e., negative anomaly values were observed along the western boundaries of the park and Mexico border; **Figure 4**). Also, larger negative anomaly values were more geographically widespread than positive anomalies, which generally occurred in clusters. This negative trend has occurred in the majority of anomaly values in more recent years (**Appendix Figure A3**), consistent with negative percent change in EVI values previously noted (**Figure 2B**). When mapped, we identified negative anomaly values in the southwestern portions of the park with relatively smaller areas experiencing positive EVI anomalies (**Figure 5**).

Increased metrics of human activity or influence (i.e., artificial light and human footprint) were found in a location consistent with a local oil refinery and in areas that are uncharacterized for human development. Analysis of burned areas revealed that fires have been present throughout the national park during the study period with notable, consistent burning observed in the northeastern portions of the park (**Figure 6**). Nevertheless, we found weak relationships between both fire and

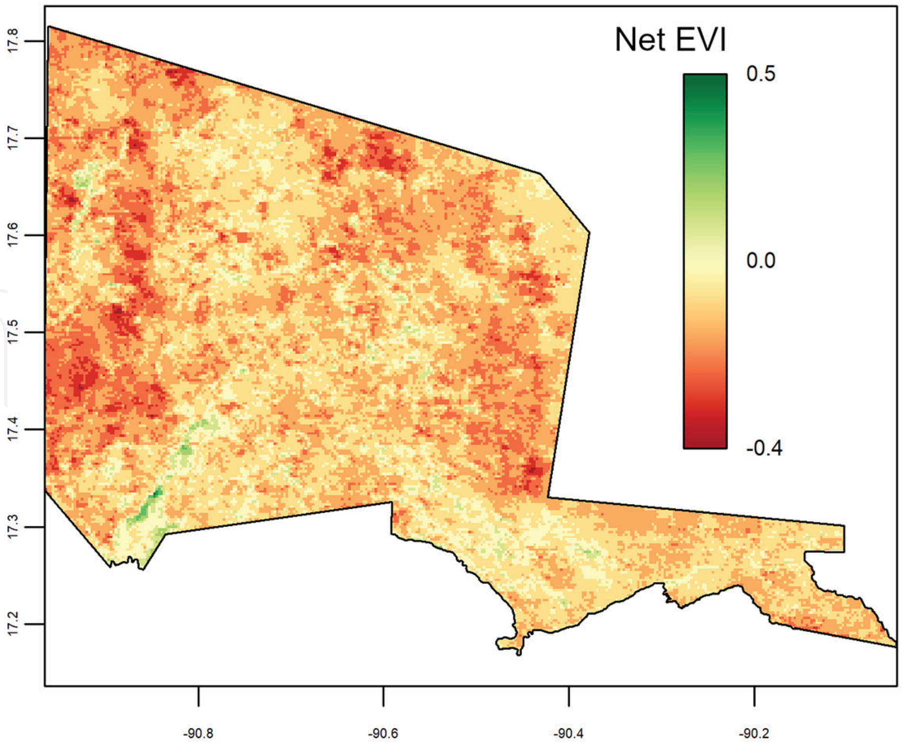

Figure 3.
Cumulative differences in raw EVI values from annual timesteps spanning 2002–2020. Annual differences (e.g., EVI values from 2004 subtracted from 2003) of raw EVI values were accumulated and summed to obtain net differences seen each year across the 18-year span. Considerable and consistent EVI loss was observed along the western border of Laguna del Tigre National Park.

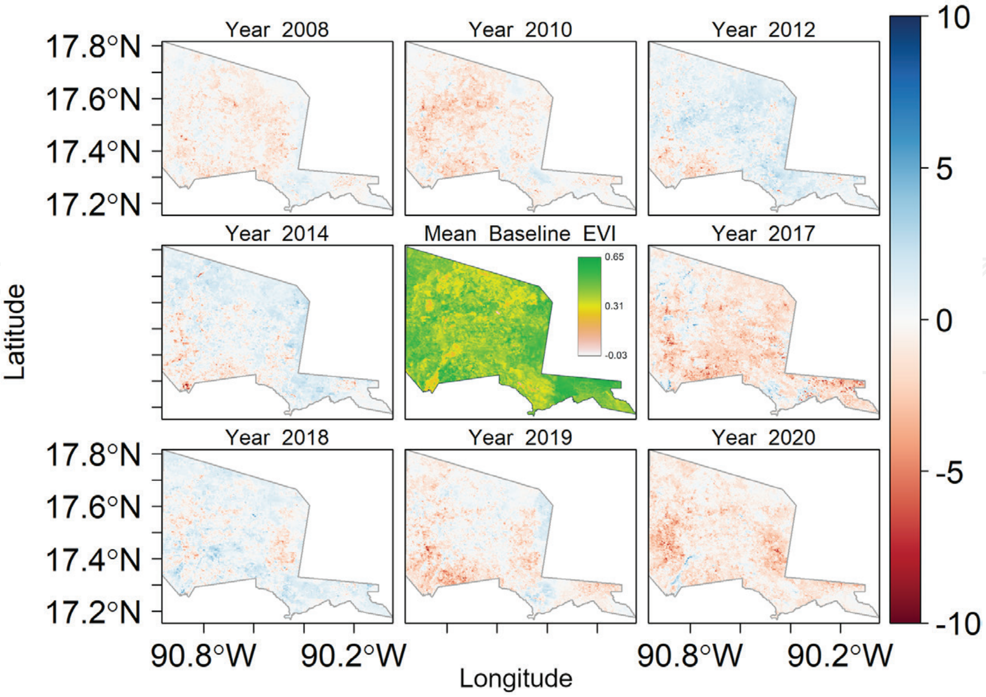

Figure 4.
Annual anomalies in EVI in Laguna del Tigre National Park. Small multiple level plots along the perimeter of plots show annual anomalies for even-numbered years. Middle plot shows the mean EVI values during the baseline (2002–2006). Anomaly values identify the number of standard deviations away from baseline variation (i.e., z-score) using years 2002–2006 as the baseline. We found negative annual EVI anomaly values (dark-red-colored pixels) were more abundant than positive anomaly values (dark-blue-colored pixels).

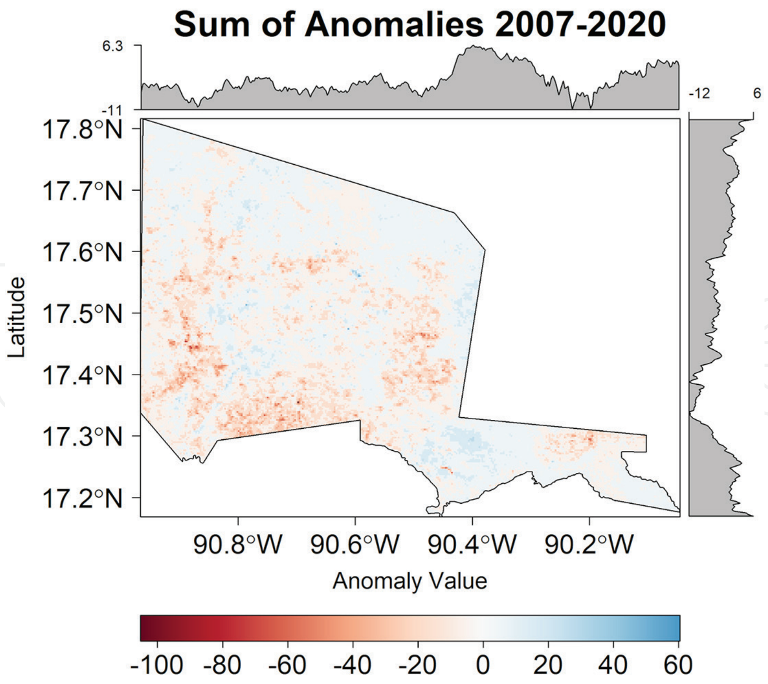

Figure 5.
Cumulative anomalies within Laguna del Tigre National Park. Map extent and black line show boundary of Laguna del Tigre National Park. Pixel colors show the magnitude of anomaly values seen from 2007 to 2020, where red colors represent areas with negative anomalies (i.e., areas experiencing negative EVI relative to baseline of 2002–2006), while blue-colored pixels identify areas with positive anomalies. We note strong signals of consistent negative anomalies in the southwestern portions of the park with relatively smaller areas experiencing positive anomalies consistent with higher EVI relative to the baseline.

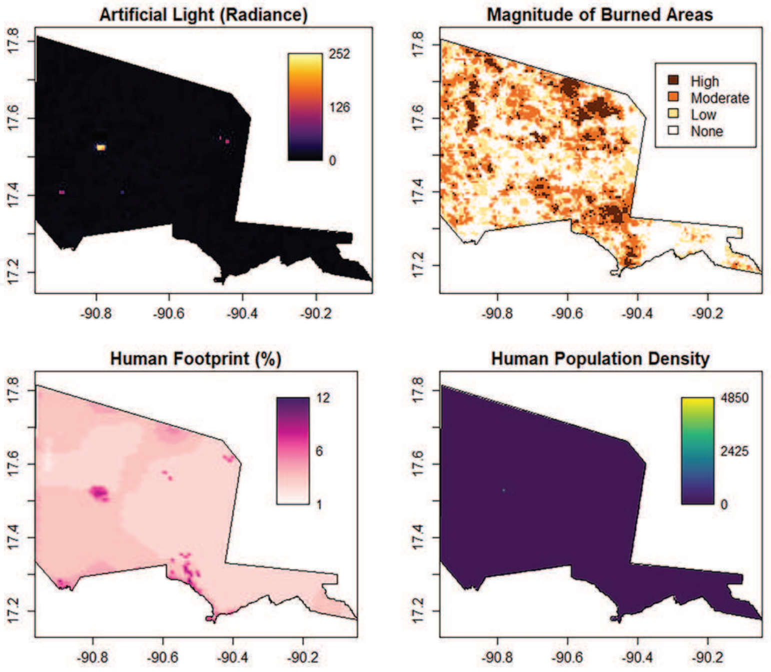

Figure 6.
Geographic distribution of variables associated with disturbance in Laguna del Tigre National Park, Guatemala. Four panels show signs of artificial light observed from nighttime light radiance (top left), magnitude of burned areas represented in categories (Jenks) (top right), percent of human footprint using methods from Venter et al. (2018) (bottom left), and human population density (bottom right). Note higher values near the center of the national park occurred at the site of a local oil refinery, while other areas of night light and burned areas were found in areas uncharacterized for human development.

published human data sources and percent change in 2020 EVI values from 2002 (R^2 values $\leq |0.26|$) (**Appendix Figure A4**).

4. Discussion

Our analyses identified anomalous losses in forest cover within the national park. This finding demonstrates that biodiversity hotspot areas are experiencing vegetative losses consistent with deforestation even inside national parks. Previous reports noted forests are cut for clandestine roads and landing strips, and drug trafficking intensifies preexisting pressures on forests by infusing already weakly governed frontiers with unprecedented amounts of cash and weapons [2]. In Guatemala's Maya Biosphere Reserve, drug traffickers deforest the protected area to illegally ranch cattle, which serves as a mechanism of money laundering, drug smuggling, and territory control [1]. From a social-justice perspective, deforestation from drug paddocks is linked to flood disasters, without forests acting as a natural "shield" against extreme weather events. Thus, indigenous communities in Guatemala are becoming more vulnerable to natural disasters. Additionally, land of indigenous communities is taken by drug traffickers [16].

We identified consistent losses in EVI within Laguna del Tigre National Park since the beginning of the twenty-first century; some losses of EVI occurred in regions where MODIS sensors revealed a history of frequent burning, and anomaly calculations have identified that many changes within recent years are uncharacteristic for the region. From 2002, the initial year of data collection and earliest available time period to the turn of the millennium when drug trafficking intensified [70], we noted that losses in EVI were becoming increasingly common throughout much of the national park. We have shown this by examining both the changes in raw vegetation index values from 2002 and by accounting for the relative weight of these changes as percentages of their initial values. Further, regions where we observed dramatic EVI losses occurred along the periphery of the national park along the Mexico-Guatemala border. Our findings are consistent with previous studies confirming forest loss within the Maya Biosphere Preserve and Guatemala in general [24, 71]. Criminal activity in the reserve in Northern Guatemala intensified at the start of the 2000s, accelerating the destruction of the western half of the reserve. An important factor is that LTNP is ideally situated to refuel drug aircrafts flying from South America and transfer narcotics to trucks for the short drive to Mexico. Ranchers have built dozens of airstrips, including one dubbed the "international airport," which had three runways, and more than a dozen abandoned aircraft, which generated a loss of 40,000 hectares of forest [72]. Drug trafficking activities in northern Central America have been facilitated by corruption in the highest authorities of local and national governments; just in the past 5 years, former presidents, vice presidents, and Security Ministers have been prosecuted or are required for extradition by the US justice system [73–75].

In general, fires in Central America have been documented for their significant variability [49]. Our analysis revealed that many areas within the national park have experienced frequent fires over the nearly two decade-long study period, consistent with past studies [71]. Identifying direct causes of fires was outside of the scope of our analyses and thus remain unknown; however, fires within this ecoregion have been recently attributed to farming practices [49] and are mostly absent from areas where official sources report human populations. Indeed, the strongest source of artificial light, reported human populations, and highest human footprint corresponds to the local oil refinery located within the park. Yet, some burned areas and strong negative anomalies in EVI loss were observed in areas where mismatches exist between artificial light being detected and a lack of official reports of human populations (i.e., areas in the southwest and northeast corners in the park), plausibly suggesting illegal settlements and slash-and-burn activities [55, 71]. In Colombia, for example, approximately more than 1 million hectares of forest have been destroyed in the production of unlawful crops. It is estimated that for every hectare of coca, four hectares of forest are damaged, most often through a crude slash-and-burn farming technique. This deforestation causes soil erosion, among other environmental problems (Foundations Recovery Network). Such mismatches observed herein geographically and correlation-wise could emphasize the need for better data on monitoring human activities in remote regions.

Some variation in forest cover within dynamic and natural landscapes can be expected, which could be identified using EVI given the variable's close relationship with climatic conditions that occur in cyclic patterns in this region (i.e., El Nino Southern Oscillation; [40]). Still, our anomaly calculations identified that recent trends in EVI values extending beyond the assumed baseline years were uncharacteristically negative, suggesting losses of vegetation. Negative anomalies were most notable along the western extent of the national park, along the Mexico border. These findings are broadly consistent with a recent spatiotemporal assessment that identified significant anomalous forest loss in Guatemala [24], but our results differ in the areas in which anomalous losses were detected, likely resulting from differences in study areas. That is, Guatemala's highest anomalous forest loss was reported in central regions of the Department of Petén [24]—a region outside of our study area; we present anomalous changes explicit to LTNP.

Our analyses are strictly descriptive to quantify dynamics in EVI that have been observed over a nearly two-decade study period. We recognize that the analyses performed provide poor capabilities on inferring causation relating narcotraffic to observed land cover change; instead, linkages between the two are supported with previous studies [2, 24] and the well-known history of criminal activities within the park [70]. Generalizability and ease of accessing data sources encourage transference of our analyses to other study areas with limited abilities to collect data *in-situ* that may be constrained by resource availability in developing countries or logistics relating to safety concerns, such as LTNP. Instead of MODIS satellite data, LANDSAT imagery could be an interesting alternative to define changes with finer scale resolution and collect local human footprint metrics in lieu of coarse scale human data that did not yield clear relationships. Our analyses serve as a local assessment of land-use change from which additional modeling activities and investigations (e.g., integrating EVI in prediction models, such as [76]) are both warranted and critically needed.

Worryingly, indigenous communities in biodiversity hotspots are being displaced from their territories due to deforestation [77]. Since 2000, deforestation rates in Honduras, Guatemala, and Nicaragua have been among the highest in Latin America and the world; after 2005, the rates increased [2]. Further, assuming conservatively that tropical primary forests support two-thirds of the wildlife species within each group, tropical forest loss/degradation will result in global richness declines of 43.8% in ants, 29.9% in dung beetles, and 19.9% in trees [78]. Examining 10 different species groups, disturbed habitats were shown to include 41% fewer species than the undisturbed forests [79]. When biodiversity does not decrease by as much as expected, a closer look can show that disturbed ecosystems become dominated by widely dispersed, highly abundant, and often invasive species such as the pig (*Sus scrofa*), black rat (*Rattus rattus*), cane toad (*Rhinella marina*), i.e., substituting endemic species for damaging ones [79].

Loss of forest coverage risks modification of the micro- and macroclimates, affecting local and broader temperature regimes, humidity, precipitation, as well creating suitable ecological niches for propagation of disease vectors and the risk of emerging infectious disease [80]. Primary forests are irreplaceable for sustaining tropical biodiversity [7]; for example, even when forest consumption halts, the habitat loss inhibits recovery of plant diversity as forests regrow [81]. For both birds and mammals, the proportion of deforestation in both insular Southeast Asia [82] and Brazil's Atlantic Forest [83, 84] consistently predicts the numbers of threatened species [5]. Even minimal deforestation has had severe consequences for vertebrate biodiversity [3]. Unless new large-scale conservation efforts are put in place to protect intact forests, deforestation rates will not slow to avert a new wave of global extinctions [3]. Current scenarios for future forest loss predict bleak futures for critically endangered species; for example, 70% loss of Sumatran orangutans by 2030 [85], as well as driving a biodiversity crisis with abrupt declines in species richness if species loss reaches a threshold from forest loss [86].

Finally, aside from cocaine transit, it is unknown how these tropical forests are impacted by other drug commodities. For example, Latin America (most notably Mexico and Colombia, and to a far lesser extent, Guatemala) now accounts for most of the heroin supply to North America (most notably the United States) [87], while also supplying smaller heroin markets of South America. Guatemala, along with Costa Rica, also has sizable cannabis cultivation [88]. Solutions need to be found to tackle challenging issues concerning drug trafficking, such as governance corruption or reducing market drivers for the demand of both cattle (imported "narco-beef") and of cocaine.

5. Conclusion

Tropical forest coverage plays a vital role in climate regulation, biodiversity, and disease prevention. Following the analyses presented here, there are numerous avenues still to investigate and questions that need clarifying. For example, can such findings lead to more effective protection of park habitat given corruption in the current political climate? Will results encourage new funding opportunities to assess whether cocaine has entered protected park borders, or to study the extent to which drug crop eradication drives deforestation by progressively displacing drug farmers into new, more remote environments? [19, 20, 77]. Further steps should address how changes in forest loss associated with drugs can motivate policy for both conservation and enforcement, how governance corruption can be curbed to limit ties of criminal organizations with elements of police, army, government, and courts, and how landscape changes to primary forest can be reduced. Clearly, interdisciplinary approaches will be needed to understand and resolve conservation problems imposed by narcotraffic within Laguna del Tigre National Park; our analyses serve as an important step in characterizing ecological changes in this biodiversity hotspot.

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A. Appendix

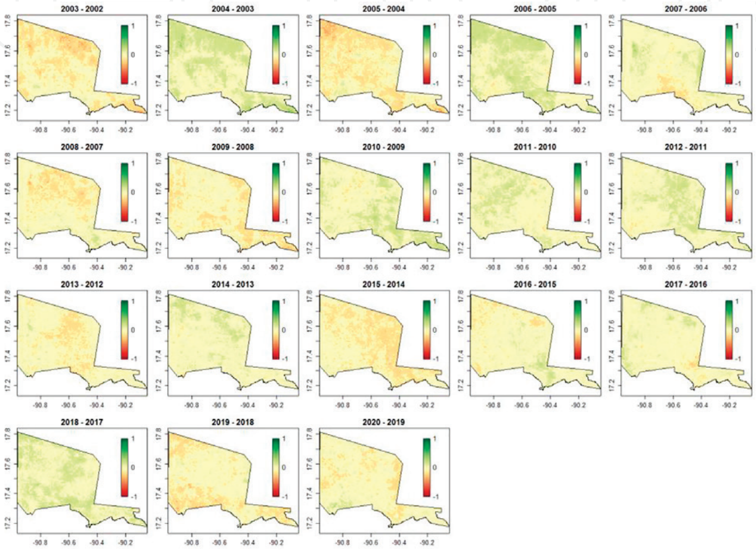

Figure A1.
Differences in EVI at annual timesteps from 2002 to 2020. Maps of Laguna del Tigre show differences in EVI in sequential annual timesteps. Red colors represent negative changes in EVI (losses), and green colors show positive gains in EVI from 1 year to the next. Each timestep displays considerable annual variation in EVI.

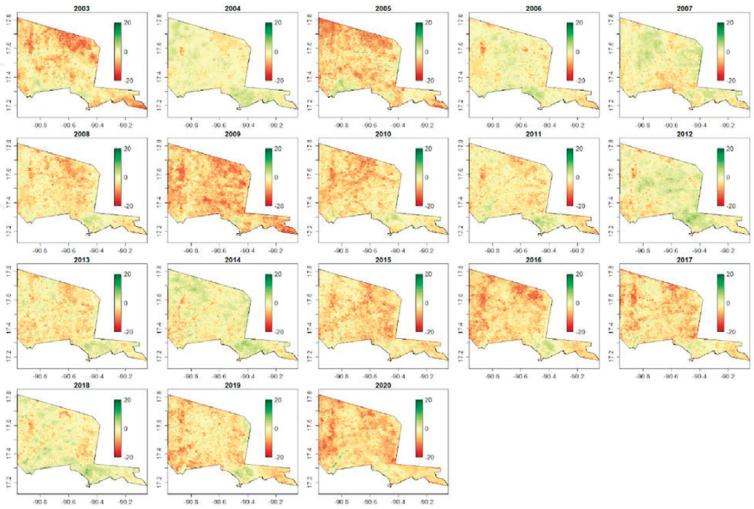

Figure A2.
Percent change in annual EVI from 2002. Changes in EVI were converted to percentages to show magnitude of change in corresponding years to EVI values observed in 2002. Colors indicate percentage increases (green) and decreases (red) in EVI relative to 2002. Note consistent and considerable decreases in EVI in the western portions of the national park.

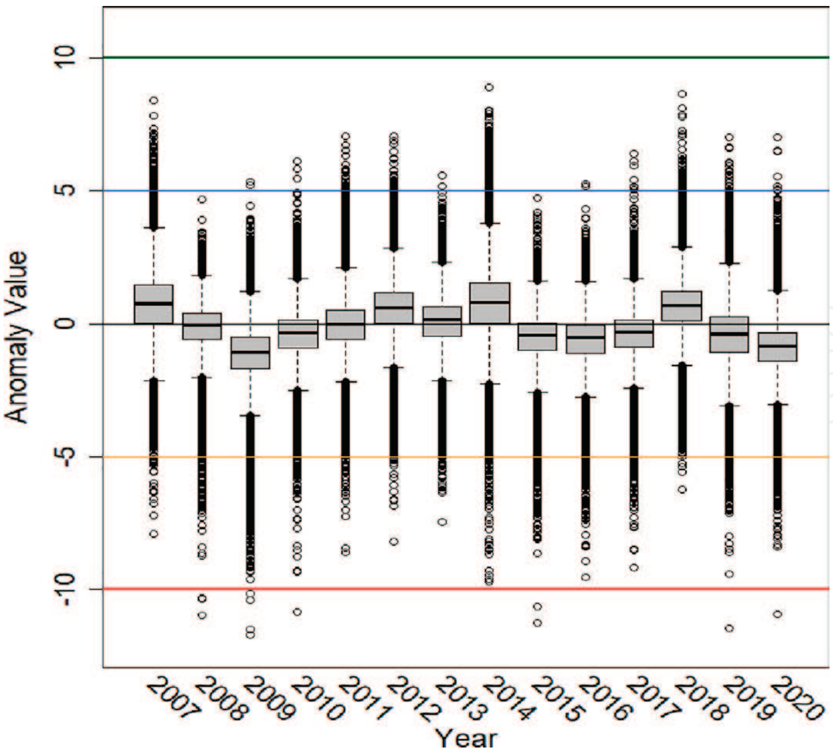

Figure A3.
Time series of anomaly values in EVI from Laguna del Tigre. Boxplots represent grouped anomaly values from yearly EVI rasters in Laguna del Tigre National Park. Years (x-axis) span from 2007 to 2020 extending beyond the baseline used for anomaly calculations (i.e., 2002–2006). Observed EVI anomalies were variable over time, though we note the high frequency of negative mean anomalies between 2015 and 2020 (83.3%).

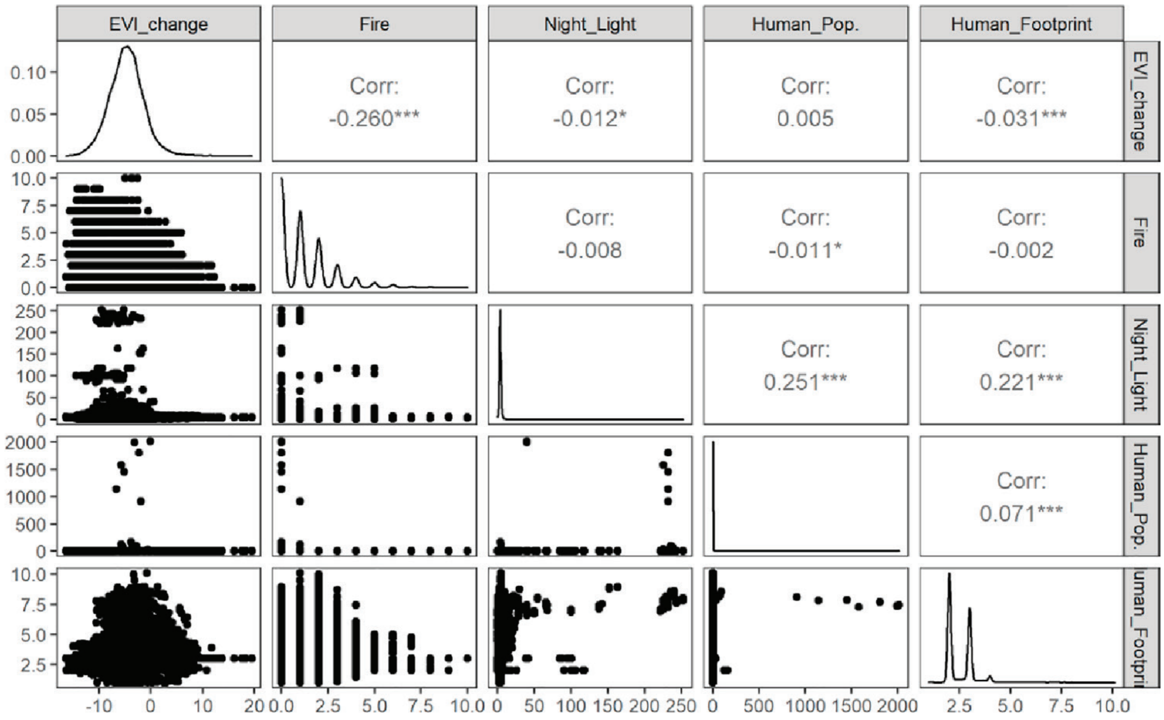

Figure A4.
Correlations between EVI change and human disturbance metrics. We found weak correlations ($R^2 \leq |0.26|$) between the percent change in EVI in 2020 from 2002, fire data, and published human data (e.g., artificial night light, human population density, and human footprint). Each subplot within pairs plot shows raw data (bottom diagonal), histogram density curves (diagonal), or pairwise Pearson's correlation coefficients (top diagonal) between variables indicated on top and far right panels.

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